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Formation of twin and double Λ hypernuclei from Ξ^- absorption at rest on ^{12}C

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1. INTRODUCTION

The absorption of a Ξ^- at rest is the most effective way to produce ΛΛ hypernuclei, which give us precious information on the low-energy YY interaction. In addition to ΛΛ hypernuclei, one finds interesting fragmentation patterns called twin hypernuclei, such as $^{12}C + \Xi^- \rightarrow {}^{4}_{\Lambda}H + {}^{9}_{\Lambda}Be$ in KEK experiment E-176 [1]. In that experiment, the probabilities of double- and twin-hyperfragment formation may be estimated to be 5∼10 % and 10∼20 %, respectively. These probabilities are very hard to understand on the basis of statistical decay models of the double-hyperon compound nucleus [2] and DWIA analysis [3], as can be seen in Table 1. Thus the experimental data suggest the importance of some dynamical effects, which cannot be mocked up by a simple escape probability for one Λ particle at the primary elementary reaction, $\Xi^- p \rightarrow \Lambda\Lambda$.

In this study, we apply a microscopic transport model, combined with a statistical decay model, to the Ξ^- absorption reaction to clarify the formation mechanism of twin and ΛΛ hypernuclei simultaneously. We adopt Antisymmetrized Molecular Dynamics (AMD) [5] with Quantal Langevin force (AMD-QL) [6], which takes into account the quantal energy fluctuations in the expectation value of energy. These fluctuations seem to be important in the Ξ^- absorption reaction in which the excitation energy is very small (≈ 3MeV).

2. MODELS

The starting point of our model is AMD [5]. In AMD, the quantum states are constructed by the following Slater determinant of Gaussian wave packets.

$$|\boldsymbol{Z}\rangle = \frac{1}{\sqrt{A!\,\det \boldsymbol{B}}} \det\left[|\boldsymbol{z}_i(\boldsymbol{r}_j)\rangle\right] , \tag{1}$$

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$$|\boldsymbol{z}_i(\boldsymbol{r}_j)\rangle = \left(\frac{2\nu_i}{\pi}\right)^{3/4} \exp\left[-\nu_i(\boldsymbol{r}_j - \boldsymbol{z}_i/\sqrt{\nu_i})^2 + \frac{1}{2}\boldsymbol{z}_i^2\right] \chi_i(j) \ , \ B_{ij} = \langle \boldsymbol{z}_i|\boldsymbol{z}_j\rangle \ , \tag{2}$$

where χ_i represents the spin-isospin wave function and the parameter ν_i is (inversely) related to the variance of the Gaussian wave packet; both are assumed to remain constant in time. The real and imaginary parts of the parameter $\{\boldsymbol{z}_i\}$ of the Gaussian wave packet (2) include the mean position $\boldsymbol{d}_i$ and the mean momentum $\boldsymbol{k}_i$, respectively. Applying the time-dependent variational principle to the total wave function $|\boldsymbol{Z}\rangle$, we obtain the equation of motion for the paramters $\{\boldsymbol{z}_i\}$,

$$\dot{\boldsymbol{z}}_i = \frac{i}{\hbar}\boldsymbol{F}_i \ , \quad \boldsymbol{F}_i = -\sum_j C_{ij}^{-1}\frac{\partial \mathcal{H}}{\partial \bar{\boldsymbol{z}}_j} \ , \quad C_{ij} = \frac{\partial^2 \log\det \boldsymbol{B}}{\partial \bar{\boldsymbol{z}}_i \partial \boldsymbol{z}_j}. \tag{3}$$

Here, $\mathcal{H} = \langle \boldsymbol{Z}|\hat{H}|\boldsymbol{Z}\rangle$ is the expectation value of the total energy. The above equation of motion describes the motion of particles in the mean field. In addition to the equation of motion, a two-body collision term, which describes two-body collisions allowed by the Pauli principle, is included. The collsion term partially describes fluctuations from the mean field. These fluctuations are considered to be indispensable for a description of the fragmentation process. In Ξ^- absorption reactions, various kinds of fragmentation such as Λ hypernucleus formation with Λ emission, $\Lambda\Lambda$ hypernucleus formation, and twin hypernuclei, from the fragmentation into two Λ hypernuclei, are observed. Then we need large fluctuations to describe these fragmentation processes. However, in the Ξ^- absorption reaction, fluctuations caused by the two-body collision term are largely suppressed by the Pauli principle since the excitation energy of this reaction is very small. Therefore, we need different sources of fluctuations to describe the experimentaly observed fragmentation.

Recently the Quantal Langevin model (QLM) [6] has been developed to incorporate the inherent energy fluctuations of wave packets, such as the Slater determinant of Gaussian wave packets, since they are time-dependent and not the energy eigenstates. In this work, we take into account these inherent energy fluctuations for dynamics as the source of fluctuations from the mean-field evolution. In detail, following the QLM, we modify the AMD equation of motion to the Langevin type equation as follows.

$$\dot{\boldsymbol{z}}_i = \frac{i}{\hbar}\boldsymbol{F}_i + \beta'_{\mathcal{H}}\sum_{kl} g_{ik}g_{kl}\boldsymbol{F}'_l + \sum_k g_{ik}\boldsymbol{\zeta}_k \ , \quad \beta'_{\mathcal{H}} = \frac{\mathcal{H} - E}{\sigma'^2_E} \ . \tag{4}$$

The stochastic term which includes white noise ζ appearing here is referred to as the *Quantal Langevin* force and this gives the energy fluctuations for the system. Here, we remove the energy fluctuations related to the fragment centre-of-mass motion and we employ the matrix $\boldsymbol{g}$ that contains off-diagonal parts reflecting single-particle overlaps so that the energy is unaffected by the fluctuation for fragments close to their ground states. We call the resulting model AMD-QL. We describe the dynamical process of the Ξ^- absorption reaction with AMD-QL while the decay of excited fragments appearing after the dynamical process is described by the multi-step binary statistical decay model denoted as Cascade.

3. RESULTS FOR THE Ξ^- ABSORPTION REACTION

The initial wave function of the Ξ^- particle is calculated by assuming the interaction between Ξ^- and ^{12}C to be a Woods-Saxon potential and the Coulomb potential [4]. In this study, we assume that the Ξ^- is absorbed from a p state and that the strength of the Ξ^--^{12}C Woods-Saxon potential is $V_0 = -16$ MeV. Once the Ξ^- wave function is known, the absorption point of the Ξ^- is calculated by the density overlap between protons in ^{12}C and the Ξ^-. In AMD-QL, the expectation value of energy can fluctuate due to the Langevin force. This fluctuation comes from the energy dispersion of wave packets and can be large in the strongly interacting region. Therefore, we also allow for energy fluctuation in the initial $\Xi^- p \to \Lambda\Lambda$ elementary process. Specifically, initial momenta of two Λ's are chosen to be those in a free space, for simplicity.

In the AMD simulation, two Λ particles are easily absorbed into the compound nucleus since Λ particles easily lose most of their single-particle energy due to collisions with other nucleons. In AMD this kind of energy loss frequently occurs and $\Lambda\Lambda$ compound nucleus formation becomes dominant (80.3 %).

On the other hand, due to the energy fluctuation present in AMD-QL, the Λ emission probability is drastically enhanced and the probability for $\Lambda\Lambda$ hypernuclei decreases (to 11.4%) in the dynamical process. The mechanism of Λ emission is as follows. When the two Λ particles gradually lose the single-particle energy and are going to be absorbed into the compound nucleus, one Λ is usually kicked by the Langevin force and can go outside of the compound nucleus. Then the Λ emission process dominates in the AMD-QL simulation.

A remarkable result of the dynamical AMD-QL simulation is the appearance of twin hyperfragments, $\Xi^- + {}^{12}\mathrm{C} \to {}^{9}_{\Lambda}\mathrm{Be} + {}^{4}_{\Lambda}\mathrm{H}$ (0.1%), ${}^{8}_{\Lambda}\mathrm{Li} + {}^{5}_{\Lambda}\mathrm{He}$ (0.23%), ${}^{5}_{\Lambda}\mathrm{He} + {}^{5}_{\Lambda}\mathrm{He} + {}^{3}\mathrm{H}$ (0.05%), ${}^{5}_{\Lambda}\mathrm{He} + {}^{4}_{\Lambda}\mathrm{H} + {}^{4}\mathrm{He}$ (0.1%), while no twin hyperfragment formation has been seen in the dynamical stage of AMD. In Fig. 1, we show the density evolution of a typical twin hyperfragment (${}^{8}_{\Lambda}\mathrm{Li} + {}^{5}_{\Lambda}\mathrm{He}$) formation event in the AMD-QL dynamical simulation. In the initial state, ^{12}C has a three α cluster structure. The elementary process $\Xi^- p \to \Lambda\Lambda$ changes one proton of an α cluster to a Λ. In this event, we see that a Λ picks up ^{7}Li and ${}^{8}_{\Lambda}\mathrm{Li}$ is finally produced. Most of the twin hyperfragments produced in the dynamical stage of AMD-QL directly reflect the 3-α cluster structure of ^{12}C, as in Fig. 1. These fragments are produced at an early stage of the reaction ($\sim$ 50 fm/c). In addition to twin hyperfragments, we see frequent light-fragment emission, like ^{4}He, ^{3}H, and ^{7}Li (14.1 %). We analyzed the effect of the initial energy fluctuation for the twin hyperfragment production and found that the probability decreases to one fifth of the present value if the initial energy fluctuation is not allowed. So both the initial energy fluctuation and the stochastic energy fluctuation caused by the Langevin force play significant roles for the production of twin hyperfragments.

In AMD-QL, a large fraction of dynamically produced fragments, including twin hyperfragments, have excitation energies small enough to survive the statistical decay stage because of the quantal nature of the intrinsic fragment motion. Therefore, statistical decay plays only a minor role in AMD-QL as can be seen form Table 1.

Finally, the AMD-QL (plus Cascade) calculation shows that the production of $\Lambda\Lambda$ hypernuclei is suppressed by Λ emission in the dynamical stage and directly produced twin

hypernuclei remain in the final state. These results provide a qualitative understanding of the KEK-E176 experiment.

It should be kept in mind that there are still ambiguities in AMD-QL. The key quantity concerning fluctuations, the matrix $\boldsymbol{g}$, is taken somewhat arbitrarily. Therefore, in the future, it would be of interest to determine $\boldsymbol{g}$ from a more fundamental point of view.

A serious issue recognized in this study is the large underestimatation of the formation probability of twin hypernuclei. One possibility for resolving this problem lies in a consideration of the interaction of the two Λ's. Another possibility is that the nuclear structure of ^{12}C or the level density of compound nuclear states of $^{13}_{\Lambda\Lambda}$B* is intimately related with the production of twin hypernuclei.

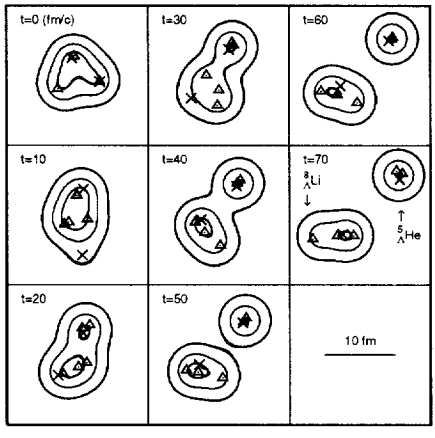

Figure 1. Time-evolution of the matter density in a typical twin hyperfragment production event, $^{12}\mathrm{C} + \Xi^- \rightarrow {}^{5}_{\Lambda}\mathrm{He} + {}^{8}_{\Lambda}\mathrm{Li}$, calculated with AMD-QL. Crosses and triangles indicate the Λ and proton positions, respectively. Neutrons are omitted for simplicity.

	Double Hyp.	Twin Hyp.
AMD-QL	11.4%	0.48%
AMD-QL +Stat. decay	11.1%	0.53%
AMD	80.3%	0.0%
AMD +Stat. decay	46.4%	2.1%
DWIA [3]	4.75%	0.11%
Statistical decay model [2]	66.0%	14.0%
Exp.	**3% ~ 10%**	**6% ~ 20%**

Table 1. Formation probability of double hypernuclei and twin hypernuclei

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